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DYNAMIC ANALYSIS OF ROBOT IN MACHINING

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ABSTRACT

This article presents analysis of kinematics and dynamics of a serial manipulator in machining process. The kinematic and dynamic models of the robot are derived and taken into account the effects of cutting forces. The method of computing the driving torques of the robot's joints to meet the requirements of the form-shaping motion of the robot is also presented. The results of the analysis and computation are validated by numerical simulation.

KEYWORDS: Robot, Kinematics, Dynamics, Trajectory Design & Machining

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Original Article

1. INTRODUCTION

Industrial robots have been used in many machining applications due to their advantages such as: high flexibility having large number of degrees of freedom that enables the end-effector of robots to easily reach to desired positions and orientations in the workspace, while processing complicated parts. With the different parts and different machining parameters, the machining capability of robots is implemented by the changeable machining programs.

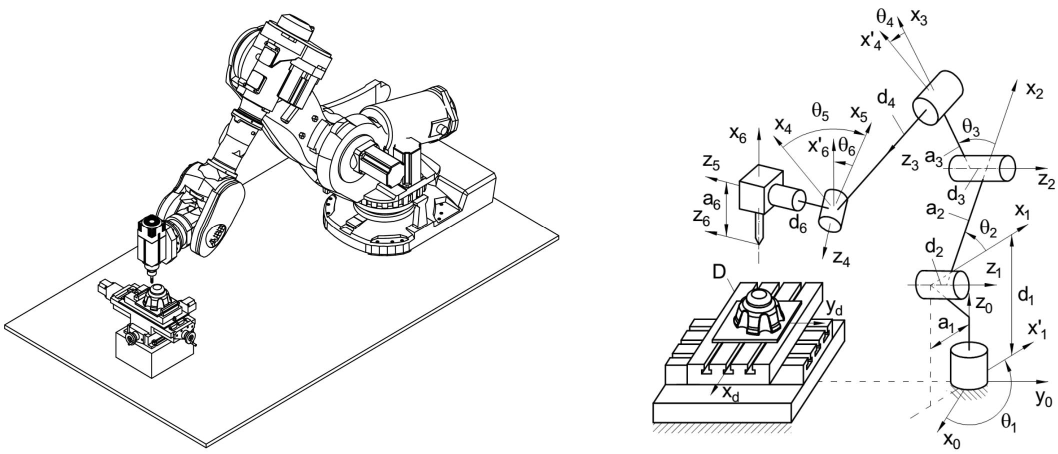


Figure 1: The ABB Robot IRB 7600-500 and its Kinematic Structure in Milling Process.

However, there are the challenges of using robots in machining process. Due to the articulated chain, with a large number of degrees of freedom, uncertain quantities, it is not easy to model and compute the dynamics of such robots. In addition, the low structure stiffness, the vibration in maching process affects accuracy of the machining parts. This paper aims to cope with the problems of modeling and computing of kinematics, dynamics, design trajectories of robot in machining, in detail. Furthermore, this paper determines the relationship of the

driving torques and the quantities of the robot's motion. The results are applied to a specific robot in milling process.

Analysis the kinematics and dynamics of the robot need to be dealt with carefully. Firstly, to guarantee the parameters of machining process, both of the relative pose and relative velocity of the cutter and the workpiece need to be met with strict rules. Secondly, as the motion of the robot's links are restricted by the kinematic and physical structure constraints, it is hard to machine large and complicated parts while trying to fulfill all requirements of the machining process. Thirdly, it is unable to calculate accurately the dynamics of the cutting process, especially the cutting forces, which act on the cutter. Fourthly, precisely determining all of the robot dynamic parameters is a challenge because of the elasticity of the joints and links, which are neglected in dynamic modeling. Fifthly, the dynamic equations are complex. These problems lead to difficulties of solving the kinematic and dynamic equations.

This paper utilizes the method of transformation coordinates, the homogeneous transformation matrices to computing and expressing the kinematic and dynamic quantities [1–5]. Lagrangian dynamic formulation is applied to derive the differential equations of motion [6–10]. The cutting forces are calculated by the formulas in [11–15]. The dynamic parameters of the robot are determined by using Autodesk Inventor software.

The paper consists of five parts. Part 1 is introduction, part 2 presents kinematic analysis, part 3 designs the trajectories matching machining engineering, part 4 analyzes dynamics of robot in machining and part 5 is the conclusion.

2. KINEMATIC ANALYSIS OF THE ROBOT IN MACHINING PROCESS

Figure 1 shows the ABB robot model IRB 7600–500 and the kinematic structure of the robot – clamping table in milling. The robot has 6 degrees of freedom, with a spindle and a cutter/ tool attaching to the end effector. The workpiece is clamped on the clamping table.

2.1 Determination of Tool's Pose Based on the Robot Kinematic Chain

Using Denavit-Hartenberg convention to assign the frames: $O_0x_0y_0z_0$ – the base frame, $O_ix_iy_iz_i$ – the frame is attached to the link i (I = 1,..,6). $O_Ex_Ey_Ez_E$ – the tool frame is attached to the cutter so that O_E is coincided with the cutting point on the cutter, x_E is tangent to the cutting edge profile, z_E is perpendicular to the cutting edge surface, y_E is defined so as to complete the right-hand rule frame. The position and orientation of the frame $O_Ex_Ey_Ez_E$ with respect to the frame $O_6x_6y_6z_6$ is determined by 6 parameters ${}^6x_E$, ${}^6y_E$, ${}^6z_E$, ${}^6\alpha_E$, ${}^6\beta_E$, ${}^6\eta_E$ (the first three parameters represent the position, the rest parameters represent the orientation of the tool). Table 1 shows the kinematic parameters of the robot.

Table 1: Kinematic Parameters of the Robot

Link	θ_i	d_i	a_i	α_i		Link	θ_i	d_i	a_i	α_i
1	θ_1	d_1	a_1	$\pi/2$		4	θ_4	d_4	0	$\pi/2$
2	θ_2	0	a_2	0		5	θ_5	0	0	$-\pi/2$
3	θ_3	0	a_3	$-\pi/2$		6	θ_6	d_6	a_6	0
The position and orientation of frame $O_Ex_Ey_Ez_E$ relative to frame $O_6x_6y_6z_6$										
E	${}^6x_E$	${}^6y_E$	${}^6z_E$	${}^6\alpha_E$	${}^6\beta_E$	${}^6\eta_E$				

Considering the robot kinematic chain: $x_0y_0z_0 \rightarrow x_1y_1z_1 \rightarrow \ldots \rightarrow x_6y_6z_6 \rightarrow x_Ey_Ez_E$, obtained the homogeneous transformation matrix ${}^{i-1}A_i$ (I = 1,..,6, E) that represents the position and orientation of link i with respect to link i-1. As a result, matrix is determined as ${}^0A_i$ that represents the position and orientation of link i with respect to the base frame $O_0x_0y_0z_0$. Matrix ${}^0A_{1E}$ (1) represents the position and orientation of the tool frame $O_Ex_Ey_Ez_E$ with respect to the base frame $O_0x_0y_0z_0$. Vector q represents joint variables (2).

$$^{0}A_{1E} = {}^{0}A_1(\theta_1)\,{}^{1}A_2(\theta_2)...{}^{5}A_6(\theta_6)\,{}^{6}A_E \tag{1}$$

$$q = [q_1, q_2, \dots, q_6]^T = [\theta_1, \theta_2, \dots, \theta_6]^T \tag{2}$$

2.2 Determination of the Tool's Pose Based on Requirements of Machining Engineering

$O_dx_dy_dz_d$ is the frame that attached to the clamping table D, and located to the base frame $O_0x_0y_0z_0$. The frame $O_dx_dy_dz_d$ is also called the jig frame. The workpiece is fixed on the clamping table, and the shape of the workpiece is expressed in the jig frame. Hence, the tool path or the path that the tool moves along the workpiece's surface is determined with respect to the jig frame. That is the reason why, we need to determine the positions and orientations of the tool with respect to the jig frame.

In this paper, the workpiece is located in the jig frame. We express the tool's pose with respect to the jig frame. Vector p represents the tool's pose with respect to the jig frame $O_dx_dy_dz_d$ at an milling instant, vector p is defined by a set of 6 parameters: (${}^dx_E$, ${}^dy_E$, ${}^dz_E$) are three position parameters, (${}^d\alpha_E$, ${}^d\beta_E$, ${}^d\eta_E$) are cardan angles. Vector p is called the operational coordinate vector.

$$p = [p_1, p_2, \dots, p_6]^T = \left[{}^dx_E, {}^dy_E, {}^dz_E, {}^d\alpha_E, {}^d\beta_E, {}^d\eta_E\right]^T \tag{3}$$

The tool's pose with respect to the jig frame $O_dx_dy_dz_d$ is represented by the matrix ${}^dA_E(p)$:

$$^{d}A_E(p) = \begin{bmatrix} c_{p11}(p) & c_{p12}(p) & c_{p13}(p) & {}^dx_E \\ c_{p21}(p) & c_{p22}(p) & c_{p23}(p) & {}^dy_E \\ c_{p31}(p) & c_{p32}(p) & c_{p33}(p) & {}^dz_E \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Table 2 shows the parameters of the base frame, jig frame and tool frame to determine the kinematic parameters of the tool's pose with respect to the base frame.

Table 2: Kinematic Parameters of the Tool's Pose, Depending on Requirements of Machining Engineering

Clamping Table's Link	${}^{i-1}x_i$	${}^{i-1}y_i$	${}^{i-1}z_i$	${}^{i-1}\alpha_i$	${}^{i-1}\beta_i$	${}^{i-1}\eta_i$
D	${}^0x_d$	${}^0y_d$	${}^0z_d$	${}^0\alpha_d$	${}^0\beta_d$	${}^0\eta_d$
E	${}^dx_E$	${}^dy_E$	${}^dz_E$	${}^d\alpha_E$	${}^d\beta_E$	${}^d\eta_E$

From the kinematic chain $x_0y_0z_0 \rightarrow x_dy_dz_d \rightarrow x_Ey_Ez_E$, one can obtain the matrices ${}^0A_d$, ${}^dA_E$, which respectively represent the pose of the jig frame with respect to the base frame and the tool's pose with respect to the jig frame, respectively. The matrix ${}^0A_{2E}$ represents the tool's pose with respect to the frame $O_0x_0y_0z_0$.

$$^{0}A_{2E} = {}^{0}A_d\,{}^{d}A_E(p) \tag{5}$$

2.3 Derivation of Kinematic Equations in Matrix Form of the Robot – Clamping Table System

The matrices ${}^0A_{1E,}$ ${}^0A_{2E}$ in (1) and (5) represent the tool's pose with respect to the frame $O_0x_0y_0z_0$, equalizing both side of (1) and (5), obtained the matrix ${}^dA_E(p)$ that determines the cutter's pose with respect to the jig frame (6):

$$ {}^{d}A_E(p) = {}^{0}A_d^{-1}\,{}^{0}A_1(\theta_1)\ldots{}^{6}A_E = \begin{bmatrix} c_{q11}(q) & c_{q12}(q) & c_{q13}(q) & {}^{d}x_{qE}(q) \\ c_{q21}(q) & c_{q22}(q) & c_{q23}(q) & {}^{d}y_{qE}(q) \\ c_{q31}(q) & c_{q32}(q) & c_{q33}(q) & {}^{d}z_{qE}(q) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6} $$

The matrix ${}^{d}A_E$ of the left side of (6) is expressed directly by the operational coordinates, denoted (3), (4). Meanwhile, in the right side of (6), the matrix ${}^{d}A_E$ is determined by the joint variables.

$$ \begin{bmatrix} c_{p11}(p) & c_{p12}(p) & c_{p13}(p) & {}^{d}x_E \\ c_{p21}(p) & c_{p22}(p) & c_{p23}(p) & {}^{d}y_E \\ c_{p31}(p) & c_{p32}(p) & c_{p33}(p) & {}^{d}z_E \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_{q11}(q) & c_{q12}(q) & c_{q13}(q) & {}^{d}x_{qE}(q) \\ c_{q21}(q) & c_{q22}(q) & c_{q23}(q) & {}^{d}y_{qE}(q) \\ c_{q31}(q) & c_{q32}(q) & c_{q33}(q) & {}^{d}z_{qE}(q) \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7} $$

The kinematic equation in matrix form (7) is used for solving kinematic problems of the robot in machining process.

2.4 Analysis of Forward Kinematics

The forward kinematics is used to determine the tool's pose with respect to the workpiece, to provide the data to control the end-effector to approach and carry out cutting processes. The joint variable vector q (q_1, q_2,… q_6) and its derivative are given by sensors, allow to compute the parameters of the tool's pose (${}^{d}x_E$, ${}^{d}y_E$, ${}^{d}z_E$, ${}^{d}\alpha_E$, ${}^{d}\beta_E$, ${}^{d}\eta_E$) with respect to the frame $O_0x_dy_dz_d$. The relative velocity, acceleration of the cutting point and the angular velocity, angular acceleration with respect to the workpiece are also computed from (7).

2.5 Analysis of Inverse Kinematics

With respect to specific machining parts, the tool paths are determined intuitively and favorably with respect to the jig frame. In machining process, the tool moves along the tool path on the workpiece by time, with the position and orientation of the tool are determined by the matrix ${}^{d}A_E(p)$, with respect to the workpiece frame. Therefore, the elements of the matrix ${}^{d}A_E(p)$ are the functions of time. The inverse kinematic problem is to determine the motion of the robot's links and the joint variables in (7). According to [2,3,4], from (7), we obtain (8), which has six independent nonlinear equations:

$$ \begin{cases} f_1 = {}^{d}x_{qE}(q) - {}^{d}x_E(t) = 0;\ f_2 = {}^{d}y_{qE}(q) - {}^{d}y_E(t) = 0;\ f_3 = {}^{d}z_{qE}(q) - {}^{d}z_E(t) = 0 \\ f_4 = c_{q11}(q) - c_{p11}(p(t)) = 0;\ f_5 = c_{q22}(q) - c_{p22}(p(t)) = 0;\ f_6 = c_{q33}(q) - c_{p33}(p(t)) = 0 \end{cases} \tag{8} $$

Where p is the vector of the tool's pose with respect to the frame $O_dx_dy_dz_d$, q is the vector of the joint variables, which are defined by (2), (3). The six independent nonlinear equations (8), with six variables q_1, q_2, …., q_6, are solved by Newton-Raphson method.

From the machining engineering, the velocity and acceleration of the tool with respect to the workpiece, the vectors of (3), (9), (10) can be determined:

$$ \dot{p} = [\dot{p}_1, \dot{p}_2, \ldots, \dot{p}_6]^T = \left[{}^{d}\dot{x}_E, {}^{d}\dot{y}_E, {}^{d}\dot{z}_E, {}^{d}\dot{\alpha}_E, {}^{d}\dot{\beta}_E, {}^{d}\dot{\eta}_E\right]^T;\ \ddot{p} = [\ddot{p}_1, \ddot{p}_2, \ldots, \ddot{p}_6]^T = \left[{}^{d}\ddot{x}_E, {}^{d}\ddot{y}_E, {}^{d}\ddot{z}_E, {}^{d}\ddot{\alpha}_E, {}^{d}\ddot{\beta}_E, {}^{d}\ddot{\eta}_E\right]^T \tag{9} $$

Derivating with respect to time the equation (8), we get the velocity and acceleration of the joint variables:

$$v=\dot{q}=[v_1,v_2,...,v_6]^T=[\dot{q}_1,\dot{q}_2,...,\dot{q}_6]^T=\left[\dot{\theta}_1,\dot{\theta}_2,...,\dot{\theta}_6\right]^T;\ a=\ddot{q}=[a_1,a_2,...,a_6]^T=[\ddot{q}_1,\ddot{q}_2,...,\ddot{q}_6]^T=\left[\ddot{\theta}_1,\ddot{\theta}_2,...,\ddot{\theta}_6\right]^T \tag{10}$$

3. DESIGN TRAJECTORIES MATCHING MACHINING ENGINEERING REQUIREMENTS

To guarantee the requirements of the machining engineering, the relative position, orientation and relative velocity of the tool and the workpiece have to match the cutting speed.

3.1 Design Geometric Trajectory

The tool path on the workpiece is the geometric path that the cutting point of the tool moves along with machining process. The tool path is expressed by a function of time or a function of ${}^dx_j$, ${}^dy_j$, ${}^dz_j$:

$${}^dx_j={}^dx_j(t),\ \ {}^dy_j={}^dy_j(t),\ \ {}^dz_j={}^dz_j(t)\ \text{ or }\ f_k\left({}^dx_j,{}^dy_j,{}^dz_j\right)=0,\quad k=1,2 \tag{11}$$

The tool path is also expressed by a set of coordinates of points with respect to the frame $O_dx_dy_dz_d$, a point has three coordinates ${}^dx_j$, ${}^dy_j$, ${}^dz_j$; n is the number of points, j is the index, j = 1,..,n.

The cutting point coordinates are expressed in the workpiece frame as follows:

$${}^dx_E={}^dx_j,\ \ {}^dy_E={}^dy_j,\ \ {}^dz_E={}^dz_j \tag{12}$$

To determine the orientation of the tool on the tool path, using the frame that bases on the geometric shape of the cutting tooth, that is the frame attaching to the tool $O_Ex_Ey_Ez_E$, which is presented above. Depending on the geometric shape of the machining part, the type of cutter and the machining conditions, the pose of the frame $O_Ex_Ey_Ez_E$ must be fulfilled for the cutting motion on the workpiece. At a cutting point on the tool path, the orientation parameters of the tool ${}^d\alpha_E$, ${}^d\beta_E$, ${}^d\eta_E$, are determined by an algorithm that bases on ${}^dx_j$, ${}^dy_j$, ${}^dz_j$. Therefore, in machining, the cutting coordinates of the tool with respect to the locating frame $O_dx_dy_dz_d$ is determined by geometric characteristic of the tool path:

$$p=\left[{}^dx_E,{}^dy_E,{}^dz_E,{}^d\alpha_E,{}^d\beta_E,{}^d\eta_E\right]^T=\left[{}^dx_j,{}^dy_j,{}^dz_j,{}^d\alpha_E\left({}^dx_j,{}^dy_j,{}^dz_j\right),{}^d\beta_E\left({}^dx_j,{}^dy_j,{}^dz_j\right),{}^d\eta_E\left({}^dx_j,{}^dy_j,{}^dz_j\right)\right]^T \tag{13}$$

The matrix ${}^dA_E(p)$ in (4), is determined at every point on the tool path:

$${}^dA_E(p)=\begin{bmatrix} c_{p11}\left({}^dx_j,{}^dy_j,{}^dz_j\right) & c_{p12}\left({}^dx_j,{}^dy_j,{}^dz_j\right) & c_{p13}\left({}^dx_j,{}^dy_j,{}^dz_j\right) & {}^dx_j \\ c_{p21}\left({}^dx_j,{}^dy_j,{}^dz_j\right) & c_{p22}\left({}^dx_j,{}^dy_j,{}^dz_j\right) & c_{p23}\left({}^dx_j,{}^dy_j,{}^dz_j\right) & {}^dy_j \\ c_{p31}\left({}^dx_j,{}^dy_j,{}^dz_j\right) & c_{p32}\left({}^dx_j,{}^dy_j,{}^dz_j\right) & c_{p33}\left({}^dx_j,{}^dy_j,{}^dz_j\right) & {}^dz_j \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{14}$$

3.2 Design Kinematic Trajectory

One of the important aspects to satisfy the machining quality and productivity is the cutting speed. This term depends on the relative velocity between the tool and the workpiece in a way such that, the velocity vector must be tangential to the tool path at every cutting point (which is determined by the machining engineering [3,4,5]).

From cutting speed function, we calculate the derivative of ${}^dx_j$, ${}^dy_j$, ${}^dz_j$ with respect to time. This is carried out by analytical method or numerical method, depending on the given tool path in term of (11), or the set of points. In general, it is expressed as follows:

$$ {}^{d}\dot{x}_j = {}^{d}\dot{x}_j(t),\quad {}^{d}\dot{y}_j = {}^{d}\dot{y}_j(t),\quad {}^{d}\dot{z}_j = {}^{d}\dot{z}_j(t) \tag{15} $$

$$ {}^{d}\ddot{x}_j = {}^{d}\ddot{x}_j(t),\quad {}^{d}\ddot{y}_j = {}^{d}\ddot{y}_j(t),\quad {}^{d}\ddot{z}_j = {}^{d}\ddot{z}_j(t) \tag{16} $$

From (12), (13), (15), (16), obtained the matrix ${}^{d}A_E(p)$, and the derivatives of its elements. Using the kinematic equation (8), we are able to compute the trajectories of the joint variables with respect to time; it means that we obtained the kinematic trajectories of the robot.

4. DYNAMIC ANALYSIS OF THE ROBOT IN MACHINING PROCESS

4.1 Dynamic Equations

The dynamic parameters of the robot are defined using Autodesk Inventor software. Table 3 shows the dynamic parameters of the links. The position of the center of gravity with respect to the frame i is C_i. m_i is mass of the link i. Inertial moment of the links with respect to the frame attaching at the center of mass is ${}^{ci}\Theta_{ci}$.

Table 3: Dynamic Parameters of the Robot

Li	C_i (mm)			m_i (kg)	${}^{ci}\Theta_{ci}$ (kg.mm^2)					
	x_{Ci}	y_{Ci}	z_{Ci}		I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{yz}	I_{zx}
Dynamic parameters of the robot										
1	395,199	-157,866	145,029	1848,496	164360156,111	228366585,197	243222507,738	8156780,510	13926827,456	40940336,294
2	-581,83	-38,201	75,771	814,880	24390416,897	78982365,424	78673161,942	-4973693,231	-1648376,169	-18784563,41
3	-67,157	33,893	-31,362	788,887	45282005,604	33499193,218	34921423,764	7137426,265	-4078491,154	1901130,489
4	-0,026	-246,497	-0,483	444,297	30557102,295	9190896,176	26143751,499	-7417,488	1151220,619	-123,128
5	0,010	0,710	87,132	96,297	1187899,191	1143345,159	600596,740	160,052	8170,999	-133,866
6	290,94	40,29	-64,09	36,306	305737,658	512275,019	383507,486	-92,536	-36,246	-41461,026

The differential equation of motion of the robot in machining is as follows:

$$ M(q)\ddot{q} + \psi(q,\dot{q}) + G(q) + Q = U \tag{17} $$

Where, M(q) is the 6x6 mass matrix of the robot; $\psi(q,\dot{q})$ is the 6x1 vector of the generalized forces of centrifugal and Coriolis forces; $G(q,\dot{q})$ is the 6x1 vector of generalized forces of the consevative forces. U is the 6x1 vector of generalized forces of driving torques of the robot. Q is the 6x1 vector of generalized forces and torques of the cutting forces.

$$ M(q) = \left[\sum_{i=1}^{6}\left(J_{Ti}^{T} m_i J_{Ti} + J_{Ri}^{T}\,{}^{ci}\Theta_{ci} J_{Ri}\right)\right]_{6\times 6};\quad G(q,\dot{q}) = [g_1, g_2, .., g_6]^T,\qquad g_j = \frac{\partial \Pi}{\partial q_j} \tag{18} $$

$$ \psi(q,\dot{q}) = [\psi_1, \psi_2, .., \psi_6]^T,\qquad \psi_j = \sum_{k,l=1}^{6}(k,l;j)\dot{q}_k\dot{q}_l,\qquad (k,l;j) = \frac{1}{2}\left(\frac{\partial m_{kj}}{\partial q_l} + \frac{\partial m_{lj}}{\partial q_k} - \frac{\partial m_{kl}}{\partial q_j}\right) \tag{19} $$

With m_i, J_{Ti}, J_{Ri} is the mass, the translation Jacobian matrix and the rotation Jacobian matrix of link i, respectively; ${}^{ci}\Theta_{ci}$ is the inertia tensor of link i with respect to the frame that is attached to the center of mass C_i, Π is energy of potential of the system, q is vector of the joint variables (2), $\dot{q}, \ddot{q}$ are the first and the second order derivative of q; (k, l;j) is Christoffel notation three indexes of the first kind; m_{kl} (k,l=1,..,6) are elements of the matrix M(q).

$$U=[U_1,U_2,..,U_6]^T=[M_1,M_2,..,M_6]^T;\ Q=[Q_1,Q_2,..,Q_6]^T=J_{TE}^T F_c+J_{RE}^T M_c=[J_{TE}^T,J_{RE}^T][F_c,M_c]^T=J_E^T R_c \quad (20)$$

Where F_c, M_C are 3x1 vectors of the cutting forces and torques acting on the cutter at the cutting point, respectively. J_{TE}, J_{RE} are Jacobian matrices ; r_E is the position vector with respect to the base frame ; F_c acts on the point E ; ω_E is the angular velocity of the end-effector. J_{TE}^T, J_{RE}^T are transposed matrices of J_{TE}, J_{RE}, respectively.

$$F_c=[F_x,F_y,F_z]^T;M_c=[M_x,M_y,M_z]^T;\ J_{TE}=\frac{\partial r_E}{\partial q};\quad J_{RE}=\frac{\partial \omega_E}{\partial \dot{q}} \quad (21)$$

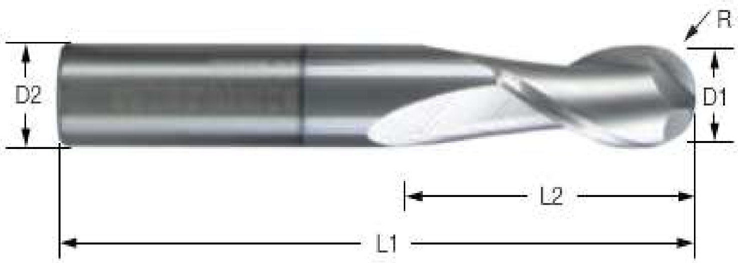
4.2 Cutting Forces in Milling Process

The cutting force depends on cutting parameters, geometric parameters of chip, cutting conditions, etc. The cutting force components are not constants because the material is not homogeneous, and depth of cut, feed rate, etc can be changed on the tool path. The cutting forces are calculated by the methods and formulas presented in [11-15]. The formular of cutting forces in x, y, z directions of Z cutting -edges are calculated as (22), where $F_{x,i}$, $F_{y,i}$, $F_{z,i}$ are cutting forces acting on the cutting edge i of the cutter.

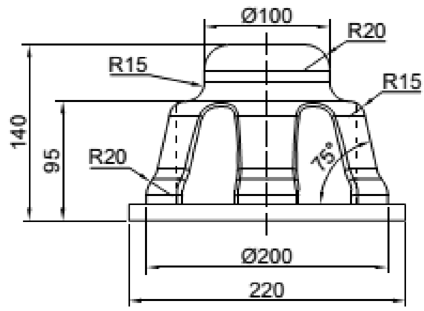
$$F_x=\sum_{i=1}^{Z}F_{x,i},F_y=\sum_{i=1}^{Z}F_{y,i},F_z=\sum_{i=1}^{Z}F_{z,i} \quad (22)$$

4.3 Computing Inverse Dynamic and Driving Torques

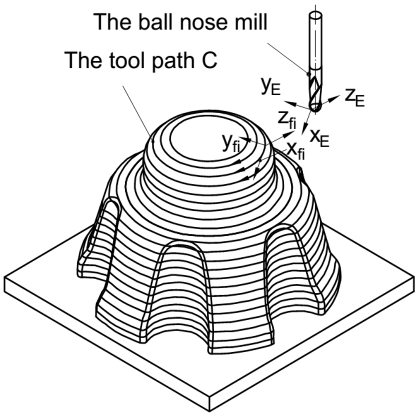
Figure 3b repesents the machining part, which made of Ti6Al4V, with the specific dimensions. The robot is utilized to carry out the down - milling operation, by using the end ball cutter, Figure 3a. Figure 3c shows the the tool path C. In milling process, the frame $x_{fj}y_{fj}z_{fj}$ is defined so as x_{fi} is the tangential line, z_{fi} is the normal of the tool path at the cutting point. At a cutting instant, the frame $x_E y_E z_E$ coincide to the frame $x_{fj}y_{fj}z_{fj}$. The frame $x_E y_E z_E$ is attached to the cutter'scutting edges, the parameters ${}^6x_E$, ${}^6y_E$, ${}^6z_E$, ${}^6\alpha_E$, ${}^6\beta_E$, ${}^6\eta_E$ with respect to the frame $x_6y_6z_6$ are determined.



a: The Ball Nose Mill



b: The Machining Part



c: The Tool Paths

Figure 3: The Cutter and the Tool Paths.

The parameters of the robot, clamping table, the cutter, and milling process are given in table 4, 5, 6.

Table 4: Kinematic Parameters of the Robot

d_1 (mm)	a_1 (mm)	d_2 (mm)	a_2 (mm)	d_3 (mm)	a_3 (mm)	d_4 (mm)	d_6 (mm)	a_6 (mm)
561	410	215	1075	215	165	1056	410	-260

Table 5: Kinematic Parameters of the Clamping Table

${}^0x_d$ (mm)	${}^0y_d$ (mm)	${}^0z_d$ (mm)	${}^0\alpha_d$ (rad)	${}^0\beta_d$ (rad)	${}^0\eta_d$ (rad)
0	-2303	202	0	0	0

Table 6: The Cutter Parameters and Parameters of Milling Process

Cutter's Material	D_1 (mm)	D_2 (mm)	L_1 (mm)	L_2 (mm)	Z (răng)	n (vg/ph)	S_z (mm/tooth)	h_0 (mm)	Cooling liquor
Carbide	8	8	63	20	2	4000	0,1	0,2	Emunxi

Where n is spindle speed, S_z is feed rate, h_0 is depth of cut. Referring to [15], cutting force coefficients in milling: K_{tc} = 1844.4 (N/mm^2), K_{rc} = 513.2 (N/mm^2), K_{ac} = 1118.9 (N/mm^2), K_{te} = 24 (N/mm), K_{re} = 43 (N/mm), K_{ae} = -3 (N/mm).

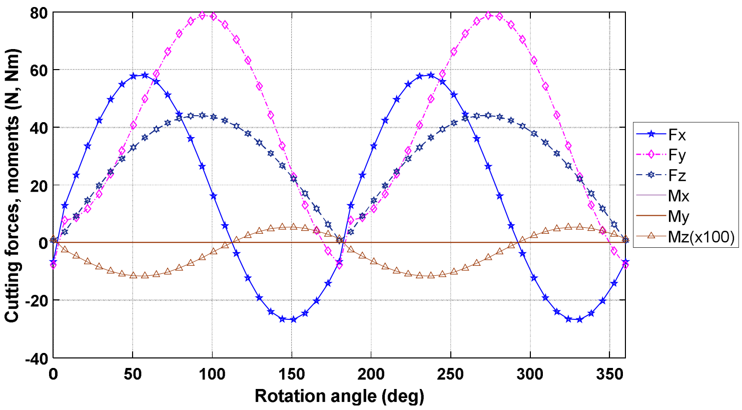


Figure 4: Cutting Forces in Milling.

The tool path C_i is a set of cutting points which are stored in a data file. To illustrate the above, this paper presents calculating the cutting forces, computing inverse dynamics to determine the driving torques of milling process of the tool path C, Figure 3.c. The tool path C is a cycle, with radius: r = 40mm. The cutting forces are computed and shown in

Figure 4. In which: the values of cutting toques are very small; the value of cutting torque M_z is 100 times; M_x, M_y are neglected.

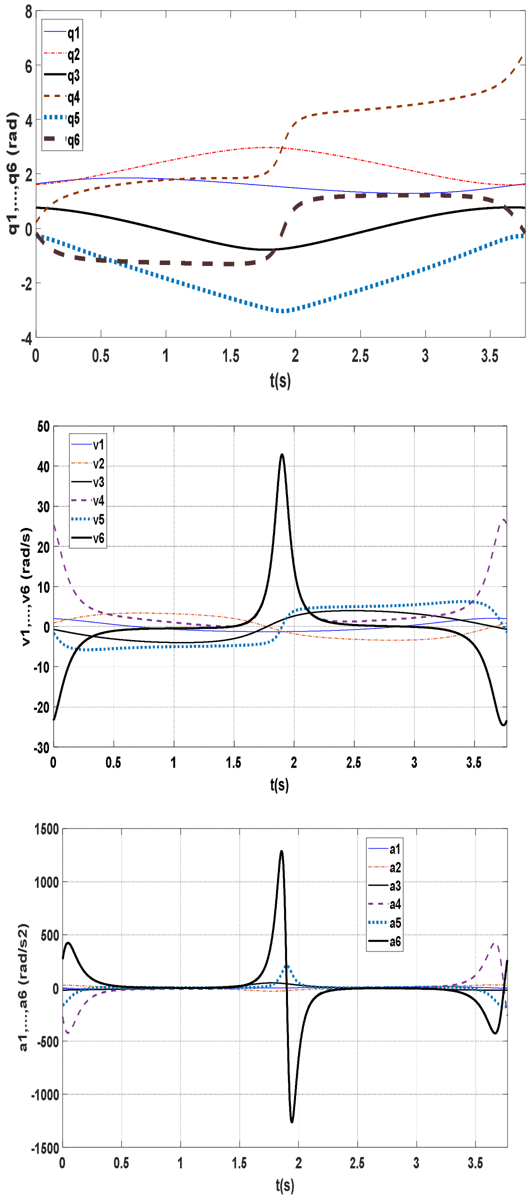
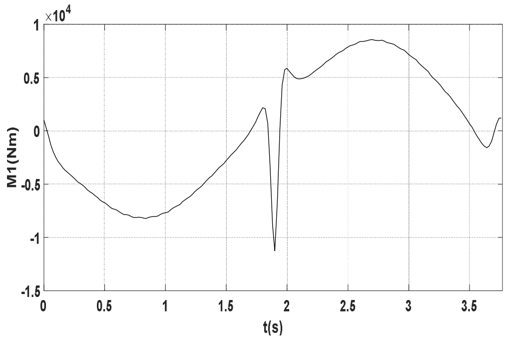
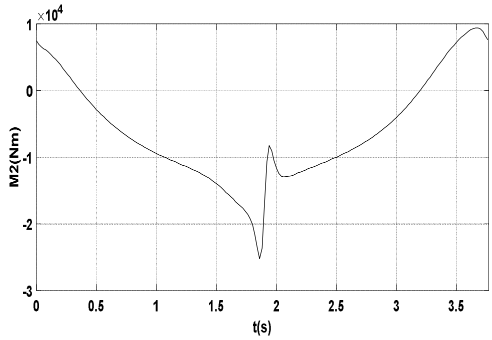
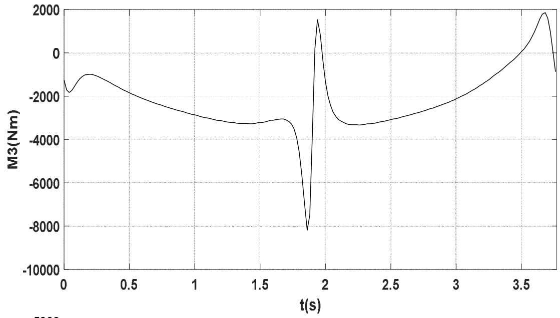


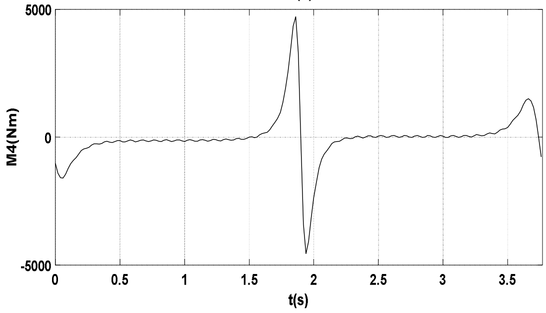
Figure 5: Time History of the Joint Positions, Velocities and Accelerations.

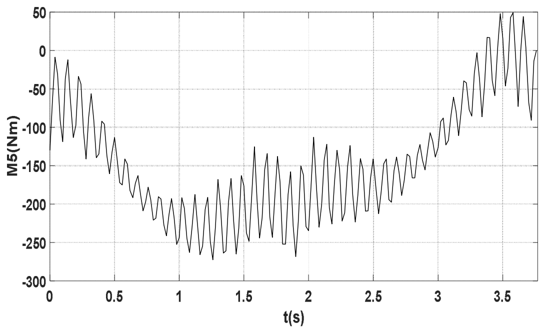
Figure 5 shows time history of the joint positions, velocities and accelerations of the robot. In which: q1,…,q6 are joint positions; v1,…,v6 are joint velocities; a1,…, a6 are joint accelerations. The results of solving inverse dynamic problem is shown in figure 6, which presents time history of driving torques at the joints corresponding to the given cutting parameters and the cutting force values.


×10^4
M1(Nm)
t(s)


×10^4
M2(Nm)
t(s)


M3(Nm)
t(s)


M4(Nm)
t(s)


M5(Nm)
t(s)

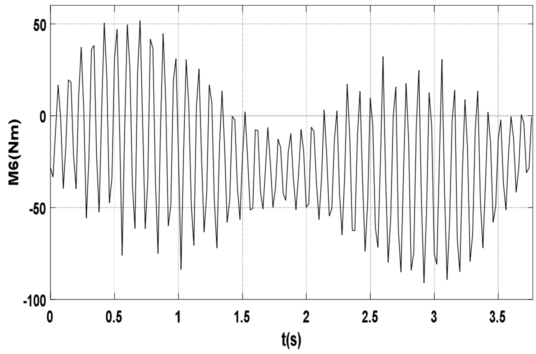
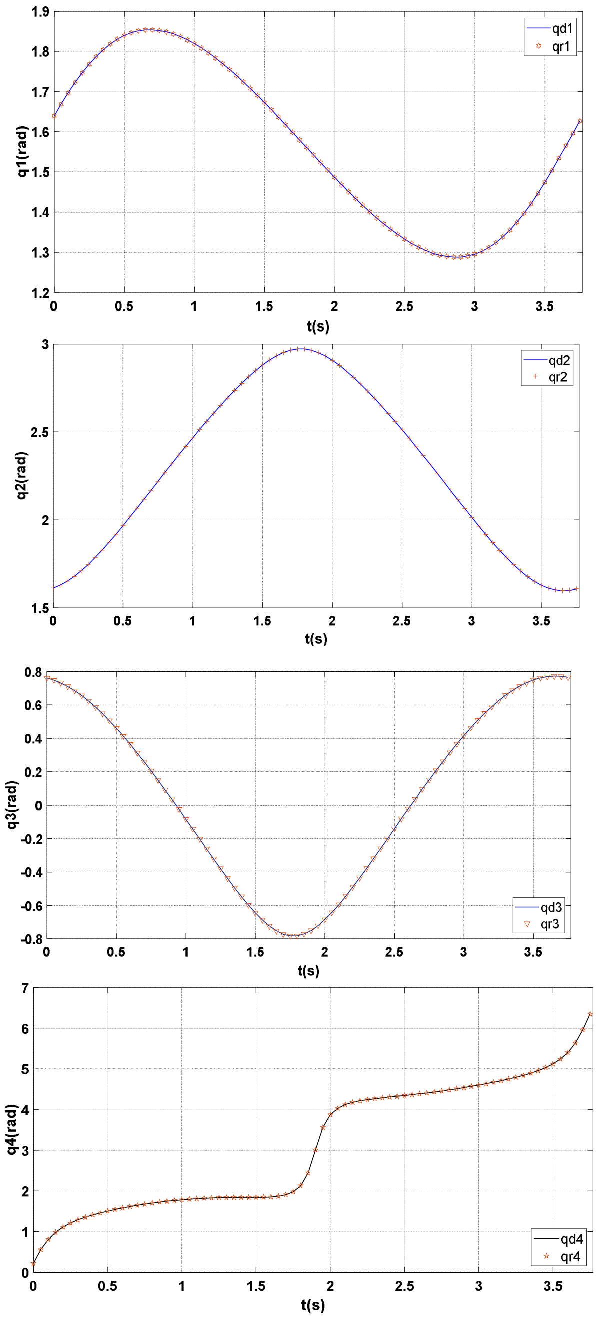


Figure 6: Time History of Driving Torques of the Robot Joints.

4.4 Computing Direct Dynamics



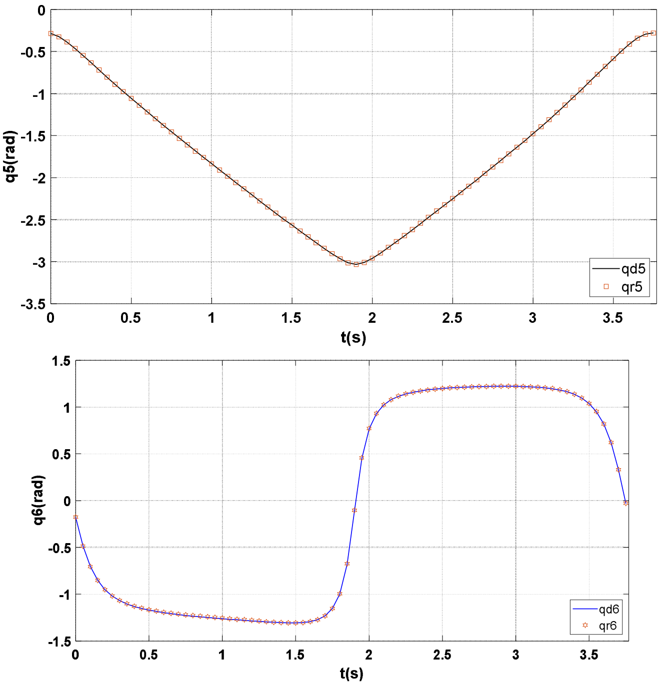


Figure 7: Time History of Joint Positions that Obtained by Designed Trajectories and Integrating the Differential Equations of Motion.

Computation of direct dynamics plays an important role. On one hand, it can determine the dynamics status of the robot, on the other hand it verifies the reliability of the driving computation and control torques of the robot in an inverse dynamics problem. From the inverse dynamics and identified driving torques, one can analyze and determine the links' motion of the robot. Figure 5 shows the design of time history of links' motion. The control torqueses are shown in Figure 6. Figure 7 presents time history of the joint positions, qd1, qd2,..,qd6 are joint positions with designed trajectories; qr1,…,qr6 are joint positions that obtained by integrating the differential equations of motion. Recognizing that the graphs exactly match together, denoting the reliability of the computed results of direct and inverse dynamics.

5. CONCLUSIONS

The derived kinematic and dynamic modelling of the serial robot in milling process enables to analyze kinematic and dynamic problems, effectively. The paper uses the transformation coordinates, the homogeneous transformation matrices, Lagrangian dynamic formulation to derive the differential equations of motion. Therefore, the motion of the robot system is only restricted by the programme constraints. In the other words, the programme motion guarantees the machining operation of the tool on the workpiece.

Due to the process forces existed between the tool and the workpiece in the differential equations of motion, it is hard to compute the generalized forces of the cutting forces. The paper utilizes the transformation coordinates, the kinematic chains of the robot and clamping table to determine the fomular of the generalized forces of the cutting forces corresponding to the generalized coordinates. The illustration is conducted on a specific robot, applying in a specific milling operation.

6. ACKNOWLEDGEMENTS

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